Parallel Processing Applied to the Design of Concrete Encased Grounding Electrodes

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Abstract

This work presents the authors' investigation regarding the application of parallel processing to the design of grounding systems, comprising concrete encased electrodes. The natural parallelism of the involved tasks and the large time-consuming characteristic of sequential processing for this kind of application justify the use of high performance computation. This design problem presents two main approaches for parallelism exploring. This work shows the advantages of parallel processing for generation of a geometric coefficient matrix, which describes the basic relations among currents and potentials at the grounding system. The grounding model has been developed at Federal University of Minas Gerais and, for implementing the parallel algorithm version, a computational tool (CPAR), which was developed in Polytechnic School of São Paulo University, was employed.

Keywords: Parallel Processing, High Performance Processing, Concrete Encased Grounding Electrode, Parallel Programming Tool.

1. Introduction

The application of high performance programming techniques for solution of Electric Power Systems problems has been increasing. Particularly, parallel processing presents very promising perspectives when heavy computation is required. It may consist in a feasible alternative for solution of several large-scale problems, which are not well conditioned for a sequential approach.

Despite its potentiality in engineering software development, parallel algorithm philosophy is quite different from that adopted by sequential programs. This picture has motivated the authors to research parallel algorithms for Electrical Engineering application in LPAD Laboratory, UFMG. Also, a specific tool for parallel software implementation (CPAR) is being developed in USP.

This work presents investigations regarding the application of parallel processing to the Design of Concrete Encased Grounding Electrodes. A set of reasons has been responsible by the development of this research: the large scale computational effort required for calculations, the inherent parallelism of the design tasks and the possibility to integrate the efforts of both research centers (Federal University of Minas Gerais and Polytechnic School of São Paulo University).

Regarding parallel processing, grounding design allows different approaches, which are being evaluated by the authors. Some of them are discussed in this text. This work is specifically dedicated to improve the performance of the tasks involved in the calculation of a matrix, corresponding to a linear system of equations. This matrix, provided by the model, describes the basic relations among currents and potentials of the grounding system.

To consider the results of the present application, the paper has been organized as follows: after this introductory section, the grounding problem is presented in section 2; section 3 discusses the different parallel approaches involved in grounding design calculation; section 4 remarks CPAR characteristics and includes its application to grounding design; simulation results are showed in section 5; finally, the conclusions of the work are presented in section 6.

2. Concrete Encased Grounding Electrodes: Basic Concept

Grounding system is an important element of electrical systems. In a very simplified way, its basic function could be considered to provide a conductive connection between electrical plant and soil.

Such system is basically composed by three components: (1) grounding electrodes (any metallic body buried in soil), (2) cables and connections (which provide electrical continuity between electrodes and electrical plant) and (3) surrounding soil (element where current derived from electrical plant is dispersed) [VISACRO 97].

During several years, the metallic parts of hydraulic systems were employed as an alternative grounding system. This practice was considered to be a worthwhile complementary solution for reducing the grounding impedance of industrial and residential electrical plants. Several years ago, around the 60's, a strong trend has begun for substitution of metallic components of hydraulic systems by insulating material (PVC). Since then, the previous practice was almost vanished and new solutions were needed for assuring improvement of grounding system performance. This has justified the present practice of connecting earthing terminations to metallic components of re-inforced concrete, which may be present in building foundations. Such system is commonly called "concrete encased grounding electrodes" [VISACRO, RIBEIRO 98].

Though such practice seems to be very efficient for several applications, the quantitative evaluation of grounding performance for this kind of system is not a simple task. The electrode is encased into concrete and, so, there is a non-direct contact among electrodes and soil, provided by concrete envelope. The low resistivity and hygroscopic properties of this material may significantly influence grounding behavior. The corresponding configuration (Figure 1) presents certain complexities, usually associated to the presence of three different materials (conductor, concrete and soil) and to its usual non-regular geometry.

This picture has stimulated the authors to investigate and to develop a computational tool, which should be able to perform the necessary calculations for such kind of grounding design. The configuration of the problem, with the conductor and concrete surface limiting borders, suggested the employment of the boundary element approach to model the grounding system [VISACRO, RIBEIRO 98].

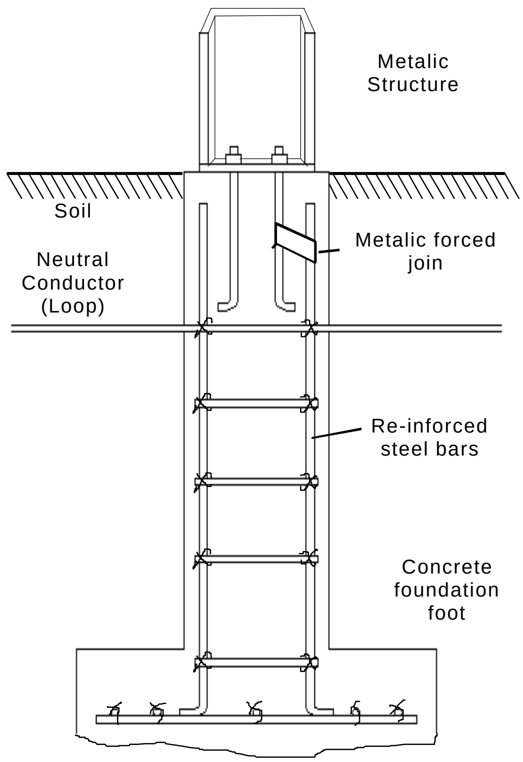

Figure 1 : Example of concrete encased grounding configuration

3. Exploring Parallel Properties in the Design of Concrete Encased Electrode

The main goal of modeling concrete encased electrode consists in determining the *Resistance* of grounding configuration and also the distribution of *Electric Potential* over soil surface, during the eventual flow of current through the electrodes. These are the fundamental parameters of practical interest in grounding design. In order to determine both of them, the model should calculate, as intermediate variables, the leakage current of each metallic segment or steel bar (current spread into concrete by them) and the current, which flows from concrete surface. By direct formulation, the grounding resistance and potential distribution may be calculated from intermediate variables.

Modeling and formulation of grounding problem are complex and are described in Appendix A. In this section, the basic steps involved in concrete encased grounding design are indicated for the aim of considering parallel processing application.

Considering this work interest and according to Appendix A developments, the grounding design involves the solution of a set of linear equation, such as:

$$Ax = b \qquad (1)$$

Where,
A: *Charge Coefficient* Matrix, determined by equation (A.12)
x: *Charge Density* Vector (h)
b: Vector of the *Electrode Electric Potential* (V)

Usually, grounding design involves the analysis of different preliminary configurations. For each one of them, a system of linear equations such as (1) is composed and solved. Grounding resistance and potential distribution over soil surface are found in each case. These parameters are employed for analyzing the performance of each configuration and for determining its improvement for achieving an optimized solution.

Figure 2 shows the flowchart with the basic steps for grounding design, which was employed in this work.

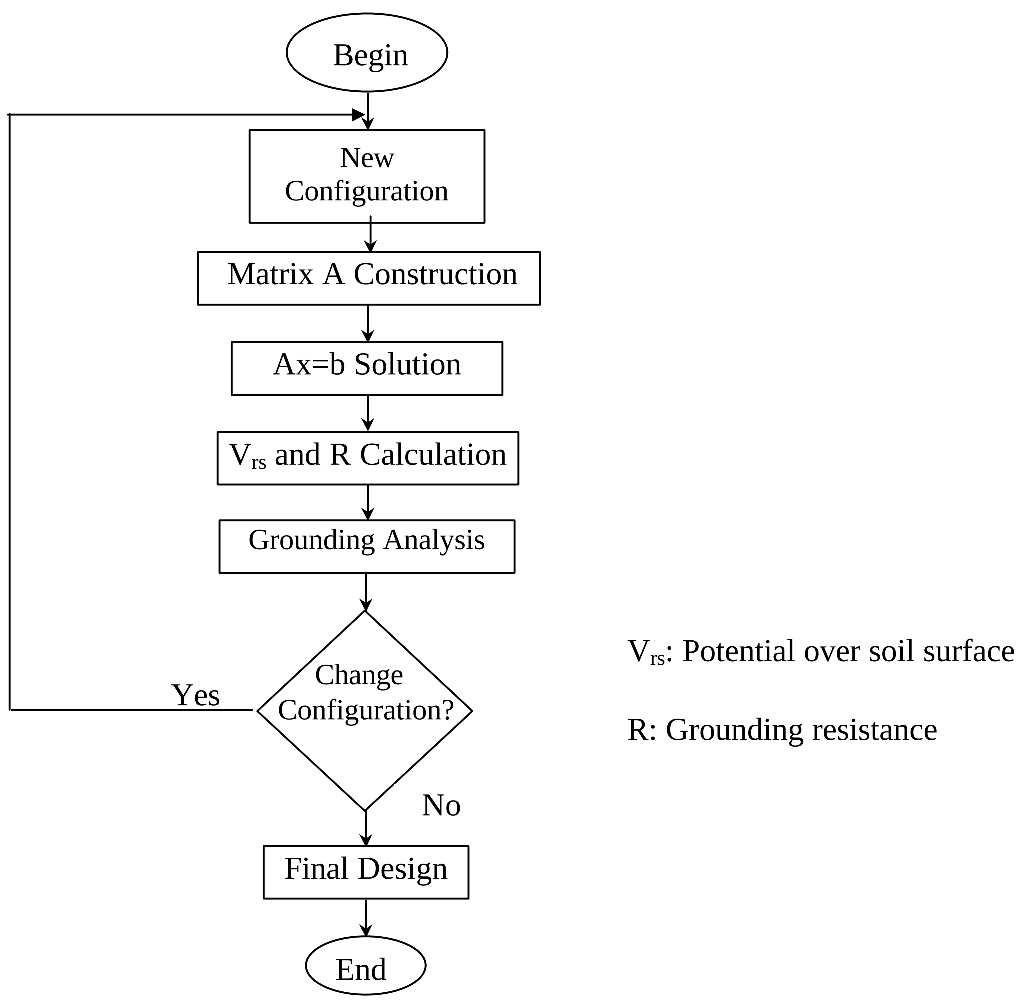

Figure 2: Flowchart with the steps of design procedure

It is immediately identified the possibility of applying parallel processing in two stages of the design procedure:

- Composition of matrix A (including calculation of its elements);
- Solution of the linear system Ax=b.

Both possibilities are compatible and may be explored simultaneously. For this work, it was decided to concentrate efforts in the investigation concerned matrix A calculation, as this stage represents a most significant challenge. Also, such application presents a remarkable parallelism for procedural tasks, which are very time-consuming for sequential algorithm version. Concerning such parallelism, all matrix elements may be independently calculated. As it is shown in Appendix, A is a full matrix and, due to the complexity of expressions employed for determining each one of its elements, the calculation is not trivial and the sequential procedure is very time-consuming.

4. Parallel Approach for Grounding Design

The fundamental activity involved in parallel processing application consists in the distribution of tasks among the available processors. The main object of this work, the construction of a linear system of equations, is very well conditioned for parallel approaches. In this section, a parallel version for matrix A construction is presented, where CPAR tool is used.

4.1 Aspects of CPAR Tool

CPAR operational facilities determined its use in this work [SATO 95]. Special constructions provided by this tool for parallel programming language make software development and implementation easier. Parallel programming requires a compromise among high performance, programming facilities and portability. Based on the balance of these parameters, CPAR was projected and implemented in such a way to permit simple construction schemes, which are able to explore multiple parallelism levels, keeping the application performance. It is an extension of C language and is based on parallel programming shared variables paradigm.

4.2 Parallelism in the Calculation of Matrix A Elements

The calculation of each matrix A element is independent and can be done in parallel. Also, the parallelism of functions used to determine such elements may be explored. On the other hand, according to Appendix A, the calculations involve two level integrals, whose processing time depends on input data. This fact makes the process to be heterogeneous with respect to the volume of operations required for each matrix element determination.

The program structure may be verified by the computational code described bellow. The main parallel characteristics are denoted.

```
for cont1=1 to number_elements
{
    ...
   sequential code
    ...
    for cont2=1 to number_elements
       switch(id6) {
             case LINE0:  swich(id7) {
                                   case LINE0:         aij=function_1(data)
                                                            ...
                                                       aij+=function_1(data)
                                   case TRIANGLE0:aij=function_2(data)
                                                            ...
                                                       aij+=function_2(data)
                                 }
             case TRIANGLE0:  swich(id7) {
                                   case LINE0:        aij=function_1(data)
                                                            ...
                                                       aij+=function_1(data)
                                   case TRIANGLE0:aij=function_2()
                                                            ...
                                                       aij+=function_2()
                                 }
             }
}
```

The computational burdens for function (function_1, function_2, function_3 and function_4) determination are very different for each set of data used as parameters. In consequence of these heterogeneous characteristics, it was decided to implement the most internal parallel loop, controlled by cont2 counter and dynamic scaling iteration [POLYCHRONOPOULOS 89]. In such scaling, once a processor finalizes an iteration, the next one to be executed is attributed to it. This parallel strategy permits a balanced load distribution that would not be obtained if static scaling was adopted (in the last case the iterations are distributed among the processors using identical size blocks).

The implemented parallel loop is showed below:

```
for cont1=1 to number_elements
   ... sequential code..
   forall cont2=1 to number_elements dsch  /*dsch=dynamic scaling*/
     {         ... calculation code ..
     }
```

5. Results and Analysis

In order to evaluate and analyze the proposed parallel strategy, two algorithms were prepared using sequential and parallel logic. The simulation was prepared in an Intel-Quad SC450NX MP, with four processors Pentium II XEON – 400 MHz, Red Hat Linux 6.2 operational system.

The performance analysis of the parallel implementation presented in this paper was prepared considering the variation of matrix dimension and number of processors. Table T.1 shows the results for each condition.

Matrix A dimension	Sequential processing	Number of processors		
		2	3	4
50	T=65	T=33 S=1.97	T=24 S=2.75	T=22 S=2.95
100	T=163	T=82 S=1.99	T=57 S=2.83	T=53 S=3.08
200	T=658	T=330 S=1.99	T=229 S=2.87	T=207 S=3.18
300	T=1 085	T=563 S=1.92	T=390 S=2.78	T=340 S=3.19
500	T=15 525	–	–	T=4 349 S=3.57

T: Processing time (s) S: Speedup

Table T1 - Performance parameters

The analysis of results shows that the parallel processing significantly improved the application performance. It is observed scalability with respect to the number of processors and matrix size. A remarkable aspect is the performance improvement when matrix size is increased. This is important if it is considered that the grounding design usually involves very large matrices.

6. Conclusion

The results show that parallel processing is a very good alternative for the design of concrete encased grounding electrodes. The adopted strategy for solution of the problem was very fitted for this application. Grounding design involves the analysis of different configurations. In each case, it requires the composition and solution of a system of linear equations. The improvement of efficiency on composing matrix A provides the possibility to analyze a larger number of potential solutions for grounding configuration and also to compute a larger number of matrix elements.

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Appendix A

Concrete Encased Electrodes: Problem Modeling and Formulation

Figure A-1 illustrates the basic elements involved in modeling concrete encased electrodes: a rectangular concrete block buried in horizontal position in the soil and comprising a cylindrical electrode inside it. The flow of electric current into the soil through the conductive electrode establishes an electric field in the region inside the concrete block and in its vicinities. The computation of such field may be performed, considering Similarity Principle, by means of equivalent surface elements of electric charge (corresponding to current elements) positioned at electrode surface. The presence of air (semi-infinite nature of soil) may be taken into account by means of a block image (including electrode). The discontinuity soil-concrete may be considered by positioning other equivalent surface elements of electric charge at the concrete boundary.

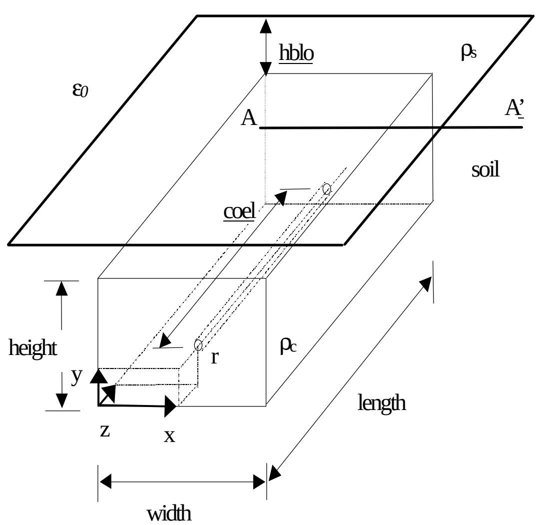

Figure A - 1   Basic grounding configuration

Equation (A.1) indicates the Electric Potential V (in reference to a remote distance), which is established by the current flow to the soil through electrode.

$$V_i = V = \iint_S \frac{h_s ds}{4pe\left|\vec{r} - \vec{r}_i\right|} \quad . \qquad \text{(A.1)}$$

In the previous integration, S represents all the surfaces that contain charge elements (electrode surface + concrete-soil interface), $\vec{r}$ is the position of any point over S, whose charge density is h_s , and $\vec{r}_i$ is the position of any point at electrode surface.

Due to Current Continuity Principle, the following relation is observed at the boundary surfaces between concrete block and soil:

$$J_{ns} = J_{nc} \rightarrow E_{ns} = \left({r_s}/{r_c} \right) E_{nc} \quad , \qquad \text{(A.2)}$$

where: J_{ns} is the normal component of current density in the soi, J_{nc} is the normal component in the concrete, E_{ns} and E_{nc} are the corresponding electric field intensity and r_S e r_C are respectively soil and concrete resistivities.

On the other hand, the following boundary condition is observed at the interface between soil and concrete:

$$D_{ns} - D_{nc} = h_{si} \quad , \qquad \text{(A.3)}$$

where: D_{ns} is the electric displacement in soil, D_{nc} the electric displacement in concrete region and h_{si} is surface charge density at point $\vec{r}_i$, which is placed at the boundary surface.

If electric displacement is substituted by electric field and current continuity is observed, it follows;

$$e_0 \left(E_{ns} - E_{nc} \right) = h_{si} \; ; \; e_0 \left(\frac{r_s}{r_c} E_{nc} - E_{nc} \right) = h_{si} \; ; \; e_0 \left(\frac{r_s}{r_c} - 1 \right) E_{nc} = h_{si} \; ; \qquad \text{(A.4)}$$

$$\left(\frac{r_s}{r_c} - 1 \right) e_0 \iint_S \frac{h_s \left(\vec{r}_i - \vec{r} \right) \cdot \vec{n}_i}{4pe_0 \left| \vec{r} - \vec{r}_i \right|^3} ds = h_{si} \quad . \qquad \text{(A.5)}$$

So, the design problem is basically described by (A.4) and (A.5). The solution consists on determining the function h_s, which satisfies these equations. From the determined solution, the electric field intensity at electrode surface is then calculated. The current density is obtained from the ratio between such electric field value and concrete resistivity. So, the current that flows to the soil is determined when current densities are integrated all over the electrode surface. The grounding resistance is calculated directly from the ratio between the known electrode potential and current values. Besides that, the same equation (A.1) may be employed for calculating the electric potential for points over soil surface.

Current Source

The current that flows through the electrodes towards soil determines an electric field distribution in both regions, soil and concrete block. This results in the establishment of an electric potential over the electrodes (in reference to a remote distance). In order to calculate such potential, the current that flows along all the electrode surface is approximated by linear source of currents supposed to be placed at electrode axis (in A/m). These are the problem independent variables. In the developed approach, the linear current sources are substituted by surface charge sources (in C/m^2). As advantage, instead of considering infinity linear sources of current, such substitution drastically reduces the number of images, which are needed to take into account the presence of concrete and soil. Only one image is needed to consider the air presence. On the other hand, each interface (boundary between different media except soil-air) requires to be modeled by additional surface charges (in this case the interface concrete-soil).

A linear current source, with length L and current density I_L (A/m), is placed at the axis of an electrode with same length L and radius r. This source generates a current density at electrode surface ($I_L/2\pi r$ A/m^2). The normal component of electric field intensity at such surface is given by $E_n=\rho c I_L/2\pi r$. As $\eta_s = \varepsilon_0 E_n$, the linear current density I_L may be calculated from ηs by the following expression:

$$I_L = \frac{2\pi r}{\rho_c \varepsilon_0}\eta_s \quad . \qquad \text{(A.6)}$$

(I_L and η_s are considered constant along electrode segment extent). The electrode is supposed to be composed by adjacent segments, each one with an independent attributed I_L value. This allows the non-uniform distribution of current along the electrode length.

System of Linear Equations

The charge surface which is represented by S in (A.1) and (A.5) is divided into small charge surfaces S_i , each one of them with an associated value for η_{si} . The electric potential on the S_i element may be determined as the sum of contributions due to all small individual charge surfaces.

$$V_i = \iint_{S_1} \frac{\eta_{s_1} ds}{4\pi\varepsilon|\vec{r}_1 - \vec{r}_i|} + \iint_{S_2} \frac{\eta_{s_2} ds}{4\pi\varepsilon|\vec{r}_2 - \vec{r}_i|} + \ldots + \iint_{S_n} \frac{\eta_{s_n} ds}{4\pi\varepsilon|\vec{r}_n - \vec{r}_i|} \qquad \text{(A.7)}$$

$$V_i = \eta_{s_1} \cdot \iint_{S_1} \frac{ds}{4\pi\varepsilon|\vec{r}_1 - \vec{r}_i|} + \eta_{s_2} \cdot \iint_{S_2} \frac{ds}{4\pi\varepsilon|\vec{r}_2 - \vec{r}_i|} + \ldots + \eta_{s_n} \cdot \iint_{S_n} \frac{ds}{4\pi\varepsilon|\vec{r}_n - \vec{r}_i|} \qquad \text{(A.8)}$$

$$V_i = \eta_{s1} \cdot A_{i1} + \eta_{s2} \cdot A_{i2} + \ldots + \eta_{sn} \cdot A_{in} \qquad \text{(A.9)}$$

If the same discretization is taken into account, but for the boundary condition expressed by (A.4), it follows:

$$\begin{aligned} \eta_{s_i} = \; & \eta_{s_1} \cdot \left(\frac{\rho_s}{\rho_c} - 1\right) \iint_{S_1} \frac{(\vec{r}_i - \vec{r}_1)\cdot \vec{n}_i}{4\pi\,|\vec{r}_1 - \vec{r}_i|^3} ds + \ldots \\ & \ldots + \eta_{s_i} \cdot \left(\frac{\rho_s}{\rho_c} - 1\right) \iint_{S_2} \frac{(\vec{r}_i - \vec{r}\,)\cdot \vec{n}_i}{4\pi\,|\vec{r}_2 - \vec{r}_i|^3} ds + \ldots \\ & \ldots + \eta_{s_n} \cdot \left(\frac{\rho_s}{\rho_c} - 1\right) \iint_{S_n} \frac{(\vec{r}_i - \vec{r}_n)\cdot \vec{n}_i}{4\pi\,|\vec{r}_n - \vec{r}_i|^3} ds \;; \end{aligned} \qquad \text{(A.10)}$$

$$0 = A_{i1} \cdot \eta_{s1} + \ldots + (A_{ii} - 1)\cdot \eta_{si} + \ldots + A_{in} \cdot \eta_{sn} \qquad \text{(A.11)}$$

When these equations are applied for each element of S, it is possible to compose a system of linear equations, expressed by (A.12). The solution of such system provides the charge density values (and corresponding current density values) and, therefore, the grounding resistance and potential distribution over soil surface.

$$\begin{bmatrix} V_1 \\ V_2 \\ \ldots \\ V_n \\ 0 \\ 0 \\ \ldots \\ 0 \end{bmatrix} = \left[\begin{array}{ccc|cc} A_{11} & A_{12} & \ldots & \ldots & A_{1n} \\ A_{21} & A_{22} & \ldots & \ldots & A_{2n} \\ \ldots & \ldots & \ldots & & \ldots \\ \hline & & & & \\ \ldots & \ldots & & & \ldots \\ A_{n1} & A_{n2} & \ldots & \ldots & (A_{nn}-1) \end{array}\right] \cdot \begin{bmatrix} h_1 \\ h_2 \\ \ldots \\ h_n \end{bmatrix} \qquad \text{(A.12)}$$